

**EXPERIMENTAL AND ANALYTICAL STUDY OF
CRYOGENIC PROPELLANT BOILOFF TO DEVELOP AND VERIFY
ALTERNATE PRESSURIZATION CONCEPTS FOR
SPACE SHUTTLE EXTERNAL TANK USING A SCALED DOWN TANK**

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SUMMARY

Self pressurization by propellant boiloff is experimentally studied as an alternate pressurization concept for the Space Shuttle external tank (ET). The experimental setup used in the study is an open flow system which is composed of a variable area test tank and a recovery tank. The vacuum jacketed test tank is geometrically similar to the external LOx tank for the Space Shuttle. It is equipped with instrumentation to measure the temperature and pressure histories within the liquid and vapor, and viewports to accommodate visual observations and Laser-Doppler Anemometry measurements of fluid velocities. A set of experiments were conducted using liquid Nitrogen to determine the temperature stratification in the liquid and vapor, and pressure histories of the vapor during sudden and continuous depressurization for various different boundary and initial conditions.

The study also includes the development and calibration of a computer model to simulate the experiments. This model is a one-dimensional, multi-node type which assumes the liquid and the vapor to be under non-equilibrium conditions during the depressurization. It has been tested for limited number of cases. The preliminary results indicate that the accuracy of the simulations is determined by the accuracy of the heat transfer coefficients for the vapor and the liquid at the interface which are taken to be the calibration parameters in the present model.

INTRODUCTION

The analytical study conducted previously [1] has demonstrated that self-pressurization due to boiloff during discharge of liquid from a cryogenic tank is possible under certain boundary and initial conditions. The boiloff phenomena depends on various parameters such as: initial pressure and temperature of the vapor, initial temperature of the liquid, initial ullage volume, discharge rate (exit valve setting), initial concentration of bubbles in the liquid, impurities in the liquid, external heat transfer, nucleation sites on the walls of the container, and variation in liquid-vapor interfacial area that are due to changes in cross-sectional area [2,3, and 4]. It also depends on parameters that are directly related to the thermophysical properties of the cryogenic fluid. It is important to know which of these parameters play an important role in determining the rate of pressure recovery in the ullage and to what extent. Such information helps one to explore the possibility of passive type of self-pressurization in cryogenic tanks.

The scope of this study includes the investigation of the important parameters that effect the self-pressurization phenomena. They are chosen to be the parameters that are set at the beginning of the discharge such as : initial ullage volume, discharge rate (exit valve setting), and initial ullage pressure. The study was planned to be conducted under a controlled environment; therefore, a scaled down model of the liquid Oxygen (Lox) tank [5] with the necessary piping and recovery system was constructed and equipped with various instrumentation in the Cryogenics Laboratory at the University of New Orleans.

A numerical analysis is also carried out to predict the time dependent pressure, temperature, density, and velocity distributions within the liquid and vapor phases of the Nitrogen in the tank as it goes through a sudden depressurization. The mathematical model adopted for this purpose is a one-dimensional, non-equilibrium thermal-hydrodynamic model. A more simplistic but practical model approach that is cited in the literature [6,7, and 8] assumes a single temperature and pressure for both of the phases. These thermal equilibrium models cannot predict the evaporation rates correctly during the initial stages of depressurization; therefore are not reliable in predicting the pressure transients. This fact may lead to underestimation (or overestimation) of the time for pressure recovery within the tank. More elaborate models use three-dimensional, incompressible Navier-Stokes equations [9] which fail to predict the transient behavior of the vapor in the ullage which exhibit non-equilibrium characteristics during the depressurization process.

DESCRIPTION OF THE EXPERIMENTAL SETUP

The schematic of the Space Shuttle Liquid Oxygen (LOx) External Tank (ET) is given in Figure 1. The tank is filled from an eccentrically placed pipe at the bottom which serves also as the outlet. The LOx tank has slosh baffles on the lower interior and anti-vortex baffles at the bottom as shown in Figure 1. The gaseous Helium is injected from the bottom of the LOx tank for geysering protection and is injected from the top for pressurization. There is also a vent/relief valve at the top of the tank. The model tank and the rest of the experimental setup is described below [10 and 11]. Nitrogen - which has thermodynamical properties similar to that of Oxygen - was chosen as the working fluid because it is safe and cheaper to obtain.

Model Tank and Flow System

The flow diagram for the experimental setup is shown in Figure 2. The setup consists of a test tank which is filled with liquid Nitrogen (LN₂) that is supplied through a 1/2 inch line from a supply tank. The 1 1/2 inch discharge line from the test tank leads to a recovery tank within five feet or to a dewar which is open to the atmosphere. The liquid line is equipped with four monitoring stations and also accommodates a cryogenic liquid pump. The recovery tank exhausts to the atmosphere through a 2 inch pipe which is also equipped with a monitoring station. The exhaust piping is designed to accommodate a cryogenic vapor blower. Both the liquid and vapor lines are equipped with ball valves to shut-off or control the flow of Nitrogen. There is a 1/2 inch Helium line which is used to pressurize the liquid in the test tank. A 1/4 inch line diverts the flow of Helium through a needle valve to the bottom of the test tank for Helium injection simulation. The gas is supplied from a high pressure Helium tank. The test and recovery tanks and all the monitoring stations have individual relief lines which open to the 2 inch exhaust line.

Test Tank: The test tank is vacuum jacketed and has a capacity of 55 gallons. The inner tank was designed in order to simulate both changing and constant liquid surface area as the liquid is drained from the tank. This is accomplished with a conical section at the top tapering out to a cylindrical mid section and a dome section on the bottom. The test tank currently has six penetrations: one 1 1/2" outlet (liquid) on the bottom, four 1/2" outlets (instrumentation ports and a vent port) and one 2" instrument port at the top. A 1/4" Helium inject port is located on the elbow of the 1 1/2" bottom outlet. In addition, two 2" viewing ports, 180 degrees apart, are located on the cylindrical section of the tank to be used in

conjunction with a Laser Doppler Anemometry and a video camera to capture the velocity and geometry of the bubbles formed in liquid during sudden depressurization. The viewing ports consist of quartz lenses attached to the inner tank and a Pyrex glass attached to the outer shell of the test tank. The test tank is made of stainless steel 304L and has a maximum operating pressure of 150 psig. Figure 3 is a drawing of the test tank.

Recovery Tank and Dewar: The recovery tank has a volume of 100 gallons in a cylindrical shape with a diameter of 28 inches. It is also vacuum jacketed. It has one 1 1/2 inch vacuum jacketed inlet at the bottom and one 1 1/2 inch outlet at the top. The recovery tank is also made from stainless steel 304L and has a maximum operating pressure of 150 psig. It is designed to stand pressures up to 150 psig. The dewar is a vacuum jacketed stainless steel tank which is open at the top. It can hold liquid Nitrogen in excess of 20 gallons.

Liquid Nitrogen Supply Tank: During the experiments, the liquid Nitrogen is supplied from a DURA-MAX 550 dewar. The dewar is vacuum jacketed and has a capacity of 55 gallons. It has a maximum operating pressure of 350 psig.

Instrumentation

The tanks and the piping are equipped with various types of instrumentation to monitor the pressure, temperature and flow rate at appropriate locations. There are five monitoring stations that are located along the liquid and vapor line. Each monitoring station has a pressure gage and a transducer, a flow-thru thermocouple, a purge valve and a pressure relief valve.

The test tank is instrumented separately to monitor the instantaneous changes in pressure in the ullage, temperature in the vapor, and temperatures at various levels of the liquid.

Pressure Gages : Analog pressure gages are placed at various points along the liquid line to visually monitor the pressures in the tanks and in the associated piping. These MATHESON cryogenic pressure gages are Bordon tube type and have a pressure range of 0 to 100 psig.

Pressure Transducers : The cryogenic pressure transducers are placed in the system as to continuously monitor the ullage pressure, the pressure of the liquid at the exit of the test tank (see Figure 4), and the pressure of the vapor in the recovery tank. They are KELLER Series 420 cryogenic transducers with a range of 0 to 100 psia and are factory calibrated for -320 deg F.

Thermocouples : Flow-thru thermocouples are placed on the tanks and on the piping to monitor the temperatures of the vapor and the liquid Nitrogen in the system. They are T type (OMEGA 304-T-MO-125), 24 WG, and shielded with stainless steel.

Another set of thermocouples are placed 2 inches (5 cm) apart on a 1/2 Teflon tubing which is suspended from the instrument port at the top of the test tank (see Figure 4). These thermocouples are T type (OMEGA TT-T-30-200), 32 WG and teflon coated, and are secured to the teflon tube by a special epoxy.

Flow Meter : A turbine flow meter is placed on the liquid line at the outlet of the test tank to monitor the flow rate. It is by SPONSLER and is designed to operate at cryogenic temperatures.

Laser Doppler Anemometer : The setup is equipped with a Laser Doppler Anemometry (LDA) to measure the velocity of the liquid particles in two directions near to the liquid-vapor interface. This will enable one to determine any circulation that may be present within the liquid, especially adjacent to the interface. The LDA can also be used to determine the velocity of the bubbles (Helium or Nitrogen). The present LDA system comprises of a 2 watts Argon-Ion laser manufactured by COHERENT, LDA optics by DANTEC which include a beam waist adjuster, retarder, beamsplitter, Brag cell, PM section, beam translator, beam expander, and front lens.

Data Acquisition Systems

Three different types of data acquisition systems are used, depending on the type of signal, to

collect and analyze the data coming from the thermocouples, pressure transducers, and the LDA photomultipliers [10 and 11].

Data Acquisition with DT2801 A/D Board : A Data Translation A/D board, T2801, is used to digitize the analog signals coming from the amplifiers that are connected to the pressure transducers. The analog signals from the KELLER cryogenic pressure transducers are amplified with HONEYWELL Acudata 218 bridge amplifiers then fed into the termination board for the DT2801. The DT2801 A/D board digitizes the signals coming from the amplifiers at a 10 Hz frequency and feeds them into the ZENITH Z-286 personal computer. Here a software called ADA processes the digitized signals and stores them in a user named data file. The stored data can be retrieved any time and plotted using the GRAPHER plotting software.

Data Acquisition with LabView : The LABVIEW software and the associated A/D board is used to collect and process the signals coming from the thermocouples. The very low potential signals are fed into a SC-2070 breadboard and then into the NB-MIO-16 A/D board. The digitized signals from the A/D board are fed into a MACINTOSH IIsi personal computer which runs the NATIONAL INSTRUMENT's LABVIEW software package. LABVIEW package is configured to display the temperatures by virtual instruments like thermometers or recordings on a strip-chart recorder. All the data that is processed by the system can be retrieved at a later time for further analysis and display.

Data Acquisition for LDA : The data acquisition system for the LDA is made by DANTEC and include two counter processors, a frequency shifter, a traversing mechanism for two-dimensional velocity measurements. The signals from the photomultipliers are fed into the counters for both channels through a frequency shifter. The processed data is fed into a ZENITH Z-386 personal computer which runs the enCOUNTER data acquisition software. This software package stores and analyzes the data and can represent the results in graphical form.

EXPERIMENTAL STUDY

The calibration of the instruments, preparation and execution of the experiments using LN₂ as the working fluid are explained below.

Calibration

It was necessary to calibrate the temperature reference junction on the A/D bread board by using a reference thermocouple which is suspended into LN₂ which is stored in a very small dewar open to atmosphere. The reference thermocouple was continuously monitored during the experiments. Furthermore, each thermocouple in the test tank was calibrated by suspending it into LN₂ under atmospheric pressure and then comparing the readings to the readings of the reference thermocouple. The maximum deviation was +/- 0.5 degrees F. The data acquisition system for the thermocouples has an overall accuracy of 0.2 degree F.

The signals from the pressure transducers were also calibrated. For this purpose the vapor Nitrogen line was equipped with a pressure transducer and a analog pressure gage. A simple calibration test was conducted where the pressure in the line was reduced slowly at a controlled rate. All the readings, including the pressure gage, multimeter, and digitized signal readings, were recorded at equal time intervals. Using these recordings, calibration curves were constructed for each pressure transducer. Third order polynomials that approximate these curves were then implemented into the software (ADA) which converts the digital readings from the A/D board to psia. The accuracy of the pressure transducers is within +/- 0.2 psia.

Experimental Procedure

The 55 gallon supply tank is filled with liquid Nitrogen one hour before the experiments start.

The pressure relief line on the supply tank is connected to the exhaust line and the valve is adjusted to keep the pressure in the tank below 300 psig. Before filling the test tank with liquid Nitrogen, the liquid and vapor exhaust lines are conditioned with liquid Nitrogen. Then the liquid Nitrogen is introduced to the test tank from the bottom with the discharge valve completely open. The vent valve at the top of the test tank is opened partially to keep the pressure in the tank lower than the pressure in the discharge line so that the liquid flows into the test tank. When the required level of liquid Nitrogen in the test tank is obtained, the 1 1/2 inch liquid outlet valve is closed. Then the liquid Nitrogen is allowed to boil until the saturation temperature at atmospheric pressure is attained. At this point the 1/2 inch vent line is closed. Then the liquid Nitrogen in the test tank is pressurized with cold Nitrogen gas to a predetermined ullage pressure. The system is ready for a blowdown experiment when the pressure and temperature of the vapor in the ullage are stabilized at predetermined values.

The experiment starts by activating the data acquisition systems. Then all the ball valves in the system except the liquid outlet valve at the bottom of the test tank are opened fully. Ten seconds after the activation of the acquisition system the discharge valve is opened to a predetermined setting in one quick stroke. The temperature and pressure readings are monitored continuously while the liquid Nitrogen discharges into the dewar or the recovery tank.

Experimental Results and Discussion

A typical history of pressure in the ullage during a sudden depressurization - TESTN41 - is shown in Figure 5. The recorded history of temperature of the vapor in the ullage (TC1) and the history of the temperatures in the liquid (TC2, TC3, and TC4) for the same experiment are shown in Figure 6. Sudden depressurization causes a drop in the recorded temperatures and then an increase as the liquid turns into vapor. The existence of temperature stratification within the liquid can be easily observed from this figure.

Three different sets of experiments were conducted to determine the effect of various operational parameters on pressure recovery. A detailed description of the experimental results can be found in reference [10 and 11].

Ullage Pressure : In one set of experiments, three different initial ullage pressures were studied: 21 psia, 18 psia, and 16 psia. The tank was full with liquid Nitrogen and the discharge valve was fully opened (90 degrees) in this set of experiments. The fluid inside the test tank was observed through the viewports during one of the high pressure experiments and has been recorded by a high speed, digital video camera. The pressure histories for these experiments as registered by the pressure transducer (PT2) located on the discharge line (Figure 4) are given in Figure 7. In all of the cases studied the pressure starts to recover after a sudden, sharp decrease in pressure.

Discharge Rate : Four different discharge rates were studied in another set of experiments. Different discharge rates were attained by setting the discharge valve to four different valve opening positions: 15, 30, 60, and 90 degrees. The pressure histories for these experiments are shown in Figure 8. The initial ullage pressure was 20 psia in all of these experiments. It can easily be observed from these figures that a slower discharge rate provides a faster rate of pressure recovery.

Initial Ullage Volume : The effect of the initial ullage volume was studied during the last set of experiments. The pressure histories for each experiment is shown in Figure 9 where the tank is filled with 50, 40, and 30 gallons of liquid Nitrogen at a time. In these experiments the ullage pressure is 20 psia and the discharge valve is fully opened. Studying these figures one observes the increase in susceptibility of the fluid to flow oscillations with increase in ullage volume.

NUMERICAL STUDY

To improve upon the numerical simulations given by the existing thermal equilibrium model [7],

it was necessary to assume the vapor and the liquid phases to be at nonequilibrium conditions which is expected to exist under sudden depressurization. Furthermore, the nonequilibrium model can be made more realistic if each phase is assumed to be made up of multiple layers of unequal temperatures. Such a model which will be referred to as "one-dimensional multi-node nonequilibrium model" is adopted for the present analytical study.

Mathematical Model

In this study the liquid and vapor phases of the cryogenic fluid in the sample tank is assumed to be separated by a well defined interface which is modelled by a film of liquid of infinitesimal thickness. The mass interaction between the phases occurs only through this well defined boundary. The location of the interface is determined by the continuity equation written for the differential volume that encloses the interface. It is assumed that vapor is located only above this interface whereas the liquid rests below.

Conservation Equations : The conservation equations of mass, momentum and energy for the liquid and the vapor phases for one-dimensional fluid flow are given by similar equations with the exception of certain terms for the liquid which are assumed to be negligible. These terms are identified by various Greek letters which take on the values -1, 0, or +1 as described in the nomenclature section of this paper.

Continuity

$$\gamma \frac{\partial}{\partial t}(\rho'_k) + \frac{\partial}{\partial z}(\rho'_k u_k) = \xi \Gamma' \quad (1)$$

momentum

$$\frac{\partial}{\partial t}(\rho'_k u_k) + \gamma \frac{\partial}{\partial z}(\rho'_k u_k^2) = \rho'_k g - \frac{\partial}{\partial z}(\theta_k P) - \tau'_w + \xi \Gamma' u_k \quad (2)$$

energy

$$\begin{aligned} c_v \left(\frac{\partial}{\partial t}(\rho'_k T_k) + \frac{\partial}{\partial z}(\rho'_k u_k T_k) \right) &= \eta \left(\frac{P}{\rho_k} \frac{\partial}{\partial t}(\rho'_k) \right) \\ &+ \eta \left(\frac{P u_k}{\rho_k} \frac{\partial}{\partial z}(\rho'_k) + \frac{\partial}{\partial z}(k \theta_k \frac{\partial}{\partial z}(T_k)) \right) \\ &+ \xi \Gamma' c_p T_k + \beta q'_{in} + q'_w \end{aligned} \quad (3)$$

where

$$\rho'_k = \rho_k \theta_k \quad (4)$$

and

$$\theta_k = \frac{A_k}{A_{ref}} \quad (5)$$

The continuity equation for the vapor or liquid adjacent to the interface for a variable differential volume is given by

$$\eta V_i \frac{\partial (\rho_i)}{\partial t} + \xi \rho_i A_i \frac{\partial (z_i)}{\partial t} + \epsilon (\rho_i u_i A_i)_m = \xi \Gamma' \quad (6)$$

Equation of State : The thermodynamic equation of state is used to close the above set of equations. For this purpose, the vapor phase is assumed to behave like an ideal gas and the liquid phase is assumed to be incompressible. Thermophysical properties of the fluid are assumed to be functions of temperature and are represented by appropriate polynomials.

Vapor generation rate : The rate of vapor generation is assumed to be a function of evaporation at the liquid-vapor interface.

Constitutive Relations for Interfacial Evaporation : The mass of evaporation term is determined from the energy balance at the interface and is given by

$$\Gamma_{ev} = \frac{-Q_{in_v} - Q_{in_l}}{h_{fg}} \quad (7)$$

where the heat transferred to any phase is given as

$$Q_{in_i} = h_{in_i} A_{in_i} (T_{amb} - T_i) \quad (8)$$

The heat transfer coefficient in the above equation is given in terms of Nusselt number which is a function of Grashof and Prandtl numbers :

$$Nu = C Gr^a Pr^b \quad (9)$$

The coefficient C in this equation is used as a calibration parameter.

Constitutive relations for Friction : The wall drag force is given by the relation

$$\tau_w = \frac{1}{8} f \rho |u| u \quad (10)$$

where the friction factor is based on the Blasius formula.

Boundary and Initial Conditions : The above governing equations are subject to the following boundary conditions for the problem under consideration: The top of the tank is closed, therefore the velocity at this end of the domain is assumed to be zero at all times which requires the continuity, momentum, and energy equations modified for zero influx of mass, momentum, and heat. The velocity at the bottom of the tank, however, is a known quantity calculated from the given (time dependent) discharge rate. The other thermodynamic properties at the exit are extrapolated from the calculated values inside the tank. Initially, the vapor and the liquid are assumed to be at rest with specified temperature and pressure distributions. The unknown properties are determined from the equation of state for each phase at the given pressure and/or temperature.

Assumptions and Limitations of the Model

Although the mathematical model is applied to a geometrically three dimensional case , i.e., the test tank in this study, the variations in thermodynamic and physical properties are assumed to be only in one dimension which is chosen to be the direction of the flow. Certainly, one expects to have variations in all three dimensions for a process that continues for minutes under nonequilibrium conditions. Also it is very possible that the initial conditions exhibit variations of properties in all directions. However, all these factors are minor compared to the role of the heat and mass transfer at the vapor-liquid interface which is basically a one-dimensional phenomena. The assumptions that the vapor is ideal and the liquid is incompressible are valid ones considering the magnitudes of temperatures and pressures attained by each phase during the initiation (and also the continuation) of the boiling process.

The ET LOx tank has some features that were not considered in this initial study. The vapor above the liquid Oxygen contains a certain amount of Helium gas. It is understood that the mixture of Helium and GOx will have different thermodynamic properties than GOx alone. However, these variations in properties do not change the magnitude of mass and heat transfer at the interface which ultimately determines the pressure and temperature of the vapor. Also , it should be noted that the effect of the Helium will substantially decrease as GOx concentration increases due to evaporation. The existence of Helium bubbles in the liquid, initially, is also ignored in this study.

Solution Technique

Finite-Difference Formulation : The numerical technique adopted to solve the governing equations under the boundary conditions given above is an explicit one which approximates the partial differential equations of the problem by finite-differences.

Discretization : The cryogenic tank (Figure 4) with a variable area section is approximated by a function given by the user of the program. This function is then used to determine the radius of each computational cell and thus the cross sectional area. The variable area section can be divided into as many cells as one wishes. A staggered spatial mesh is used in the numerical scheme. In this scheme, the fluid properties such as density and temperature are defined at the center of the computational cells, while the liquid and vapor velocities are defined at the cell boundaries. Furthermore, a dual velocity concept is used at the cell boundaries which defines a velocity just upstream and another one just downstream of the boundary [13]. The relation between these two velocities for any phase is based on the steady state mass conservation across the interface.

Finite-Difference Approximations : The basic concepts used in developing the finite-difference approximations of the governing equations are summarized below (See reference [1] for details):

(i) The mass and energy equations are approximated by forward differencing in time and space, while momentum equations are approximated by forward differencing in time and central differencing in space.

(ii) The mass and energy conservation equations are integrated from the right boundary of each cell to the right boundary of the next cell with temperature and density held constant over the length of each cell. The velocity is assumed to vary linearly within each cell between the value at the left boundary and the value at the right boundary. Momentum conservation equation on the other hand, is integrated from the center of the computational cell to the center of the next cell.

Using the above principles the governing differential equations are approximated by finite differences and then the continuity equation is solved for the future value of density, momentum equation is solved for the future value of velocity, and energy equation is solved for the future value of temperature.

Solution Algorithm

The algorithm developed to solve the present problem using the above finite-difference

approximations of conservation equations uses a specific order of calculations. First, the velocities in the liquid and the liquid-vapor interface is calculated by a backward sweep because the exit velocity is known at all times. Then the velocities in the vapor are calculated. Next, the density and then the temperature is calculated. Knowing the temperature and density, the algorithm then uses the equation of state to determine the pressures. Finally, the continuity equation at the interface is used to predict the future location of the liquid-vapor interface. The mass of evaporation, heat transfer rates at the interface and other physical properties are updated before the next set of calculations. A flow chart of the computer program is given in reference [14].

Numerical Stability Criteria : As in all explicit finite-difference techniques, the Courant stability criteria is used to obtain numerically stable solutions.

Calibration and Model Verification

The heat transfer coefficients for the liquid and the vapor at the liquid-vapor interface are chosen to be the calibration parameters of the proposed model. The value of C in Equation 9 is determined by trial and error. This is not a very difficult task because the results are very sensitive to the magnitude of these coefficients. A plus or minus 20 to 30 % deviation in the assumed values of these parameters result in physically unreasonable temperatures and/or pressures for the vapor phase.

The analytical model has been tested, by numerical experimentation, for various possible initial and boundary conditions. First, the program was run for a case where only gaseous Nitrogen existed inside the test tank. The results were comparable to the one expected for an ideal gas going through a polytropic expansion. In the next test run the evaporation rate was taken to be zero. As in the "all gas" case, the vapor phase went through a process which resembles a polytropic process. In another study the discharge was terminated after 0.5 seconds of sudden depressurization [1]. The results showed that the pressures and temperatures attained stable values very close to the ones given by the thermal equilibrium conditions. These expected results confirm the success of the model in predicting the dynamic behavior of the fluid under sharp changes in boundary conditions.

Results of the Numerical Simulations

The results of a numerical experiment (sample run), are given in Figures 10 and 11. Figure 10 shows the variation of vapor pressure in the ullage, specifically in the second computational cell, during blowdown. During initiation of boiling the pressure drops down below 16 psia then recovers mainly due to increase in evaporation, then gradually decreases. Similarly, the temperature of the vapor in the ullage decreases very sharply during the initiation of boiling then increases considerably due to increase in pressure as shown in Figure 11. It attains its maximum value around the time the pressure is maximum and then decreases gradually. The density and velocity histories were also plotted together with the distributions of each at certain time intervals.

CONCLUSIONS

An experimental study was undertaken to determine the effect of various operational parameters on the characteristics of pressure recovery for cryogenic fluids that undergo a sudden depressurization process. It is concluded that the relative discharge rate is the most important parameter that determines the rate of pressure recovery. Lower discharge rates give more time for vapor generation which increase the rate of the recovery. Initial ullage volume is important in determining the characteristics of the discharge: a high initial ullage volume amplifies pressure oscillations that exist during the blowdown. The magnitude of the initial ullage pressure effects the discharge rate therefore plays a role in the initial stages of the recovery.

The numerical analysis was carried out using a one dimensional, multi-node, nonequilibrium thermo-hydrodynamic model. This model was also used to determine the important parameters that effect the vapor generation rate during boiloff initiation and continuous boiling. In general, the numerical study also confirms the fact that self-pressurization is possible only under certain combinations of initial and boundary conditions. Various specific conclusions can be drawn from this study: The initiation of boiling is determined by the pressure and temperature of the liquid at the vapor-liquid interface. The rate of evaporation at the interface during the initiation of boiling is largely determined by the temperature gradients that exists on both sides of the interface. These gradients are determined by the rate of heat exchange between each phases. The important parameters that effect this heat exchange are the interfacial heat transfer coefficients and the interfacial area. A higher heat transfer coefficient means higher rates of evaporation which in turn means quicker recovery in vapor pressure.

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NOMENCLATURE

A	cross sectional	q	heat flux
C	constant, calibration parameter	q'	heat input per reference volume of fluid
D	diameter of the cell	Q	total heat input
f	friction factor	T	temperature
g	gravitational constant	t	time
h_{fg}	heat of evaporation	u	velocity
h_{int}	interfacial heat transfer coefficient	V	volume
k	thermal conductivity	z	spatial coordinate in axial direction
P	pressure		
Greek Symbols			
β	= 0, for all vapor or all liquid; = 1, for vapor or liquid at interface	η	= 0, for liquid; = 1, for vapor
γ	= 0, for liquid; = 1, for vapor	θ	area ratio
Γ	rate of mass of vapor generation	μ	dynamic viscosity
ϵ	= -1, for vapor; = 1, for liquid	ρ	density
ξ	= 0, for all vapor or all liquid; = 1, for vapor at the interface; = -1, for liquid at the interface	ρ'	density times area ratio
		τ	wall drag force
		τ'	wall drag force per reference volume
Subscripts			
in	interface between liquid and vapor	m	= inlet, for vapor; = exit for liquid
g	vapor phase	ref	reference
k	k th phase: liquid or vapor	s	saturation
l	liquid phase	w	wall

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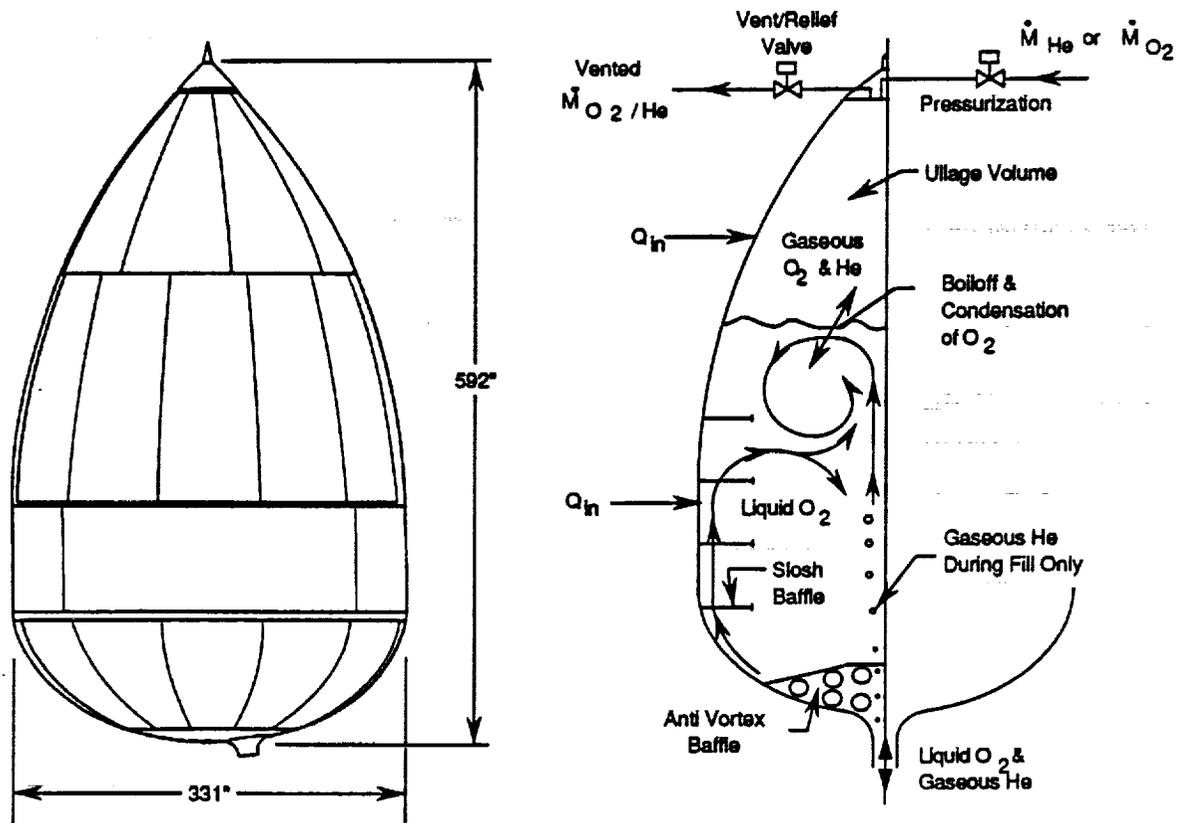


Figure 1 - Schematic of the Space Shuttle's External Liquid Oxygen Tank

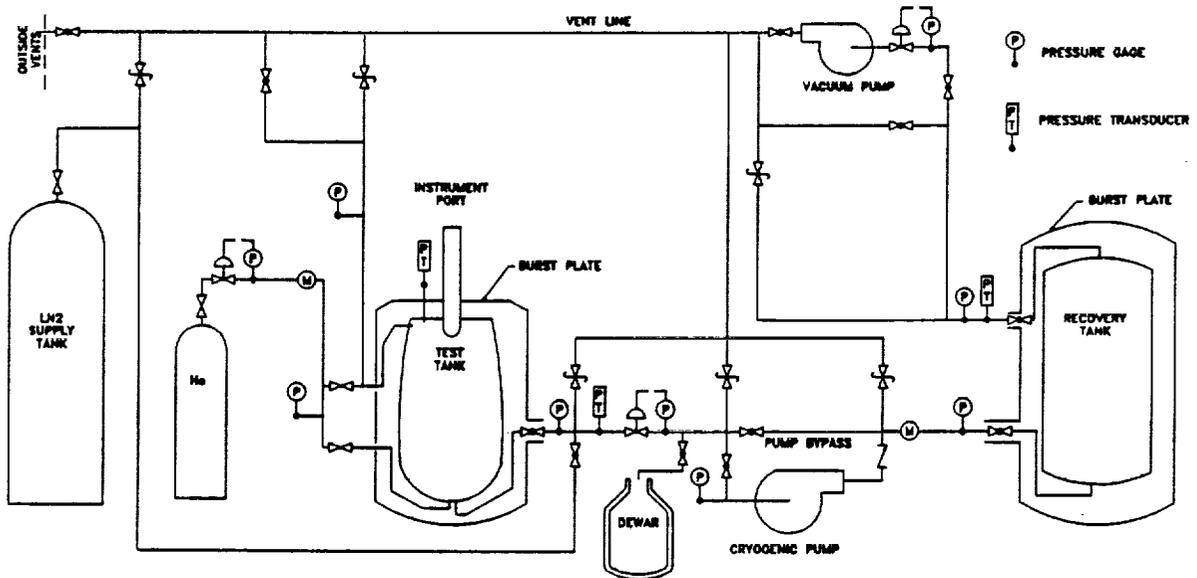


Figure 2 - Flow Diagram for the Experimental Setup

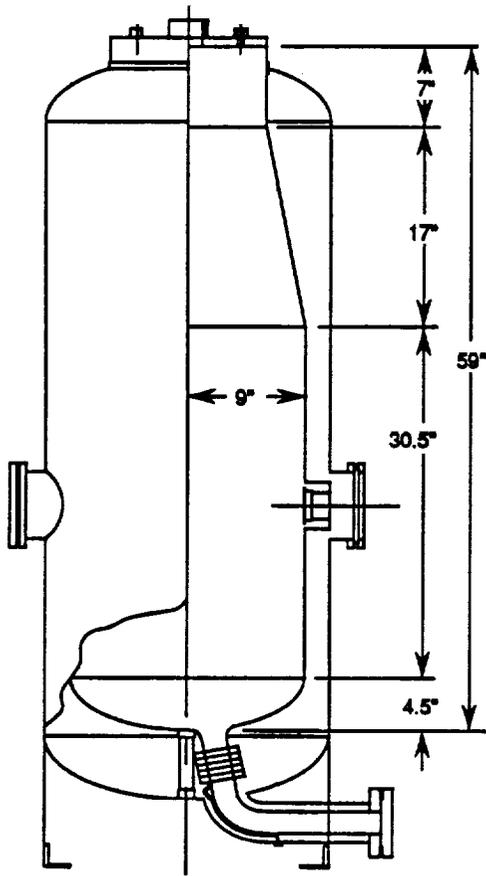


Figure 3 - Schematic Diagram of the Test Tank

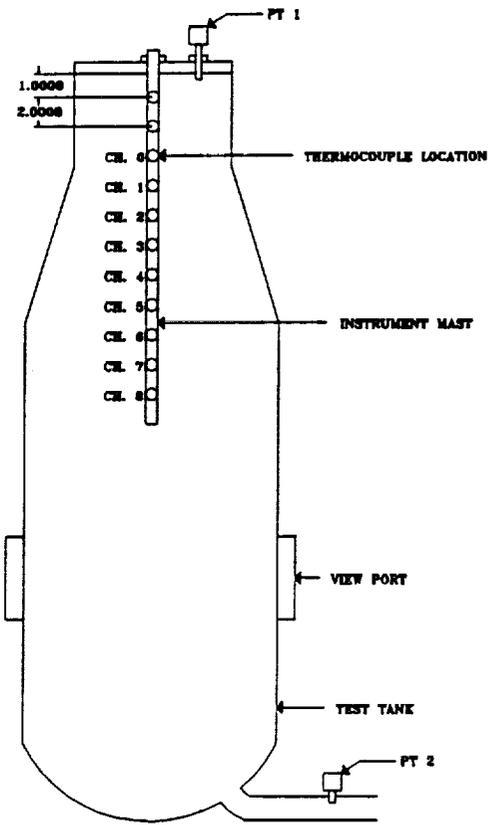


Figure 4 - Instrumentation on the Model Tank

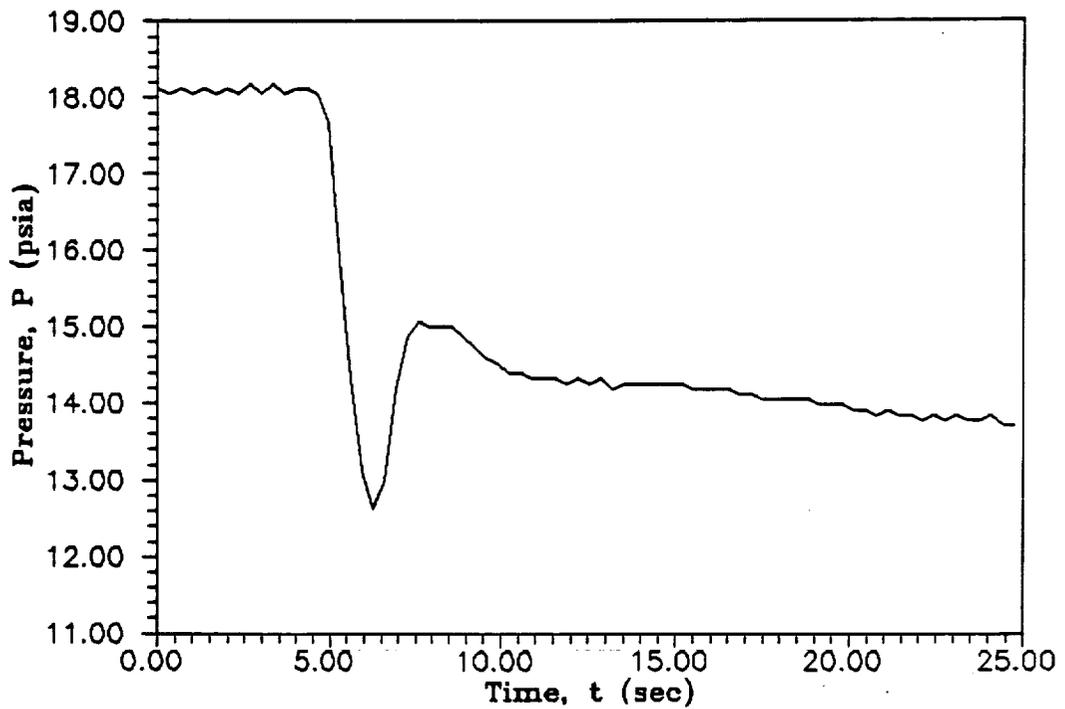


Figure 5 - Pressure Transients During Sudden Depressurization

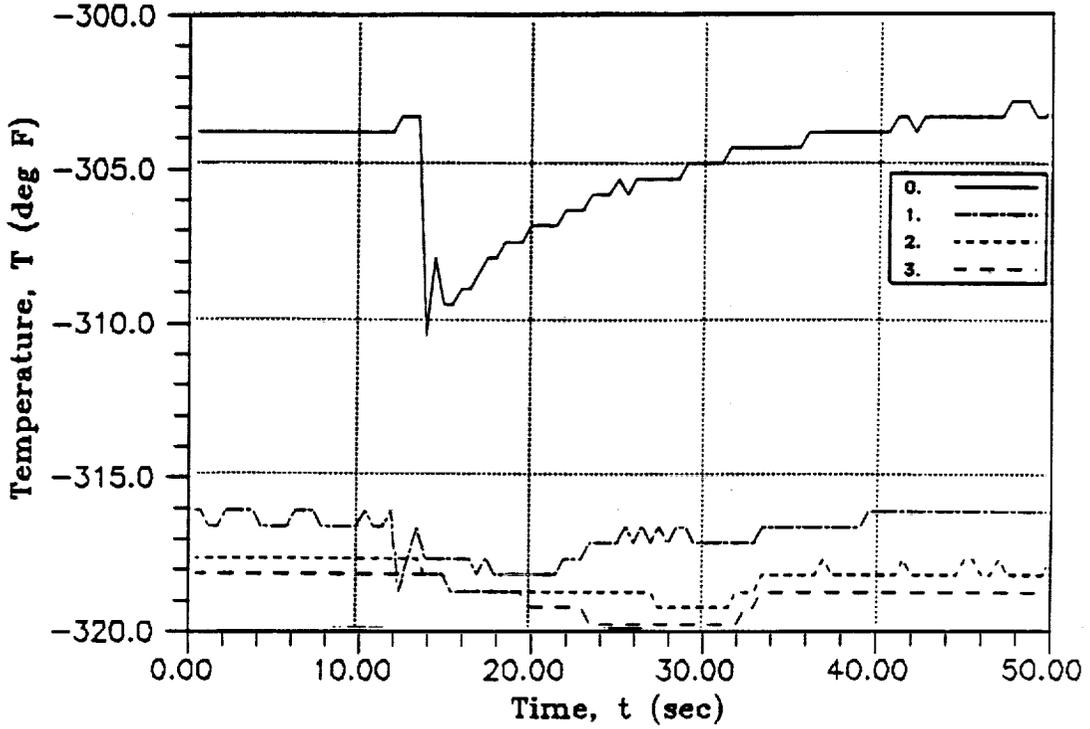


Figure 6 - Temperature Transients in Ullage During Sudden Depressurization

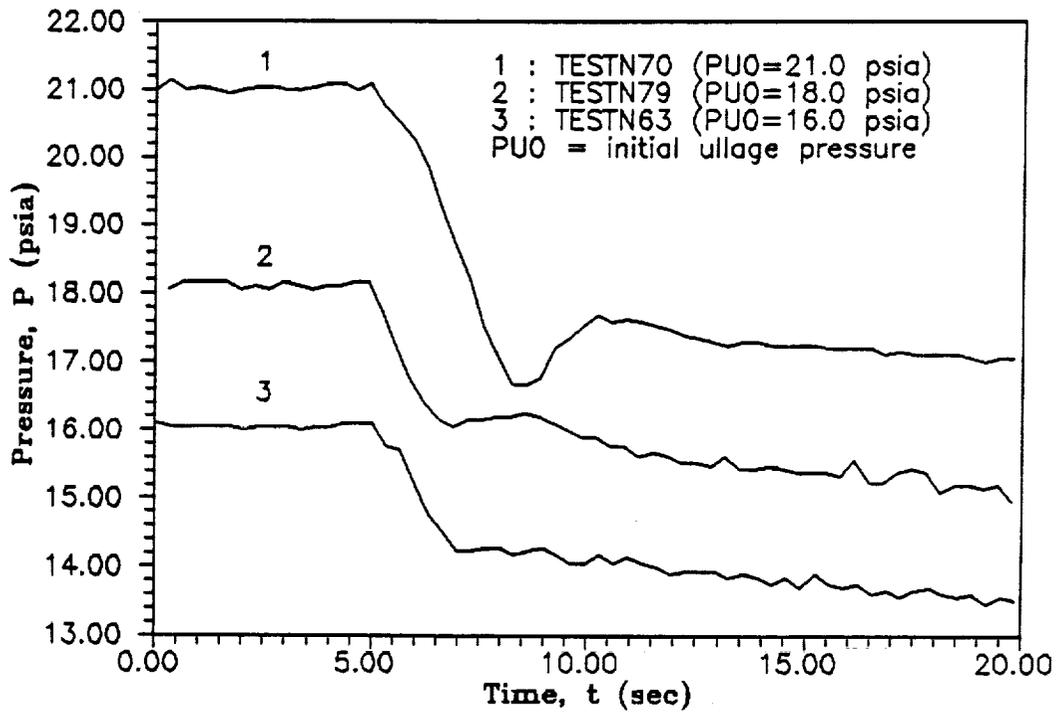


Figure 7 - Pressure Transients During Sudden Depressurization for Different Initial Ullage Pressure

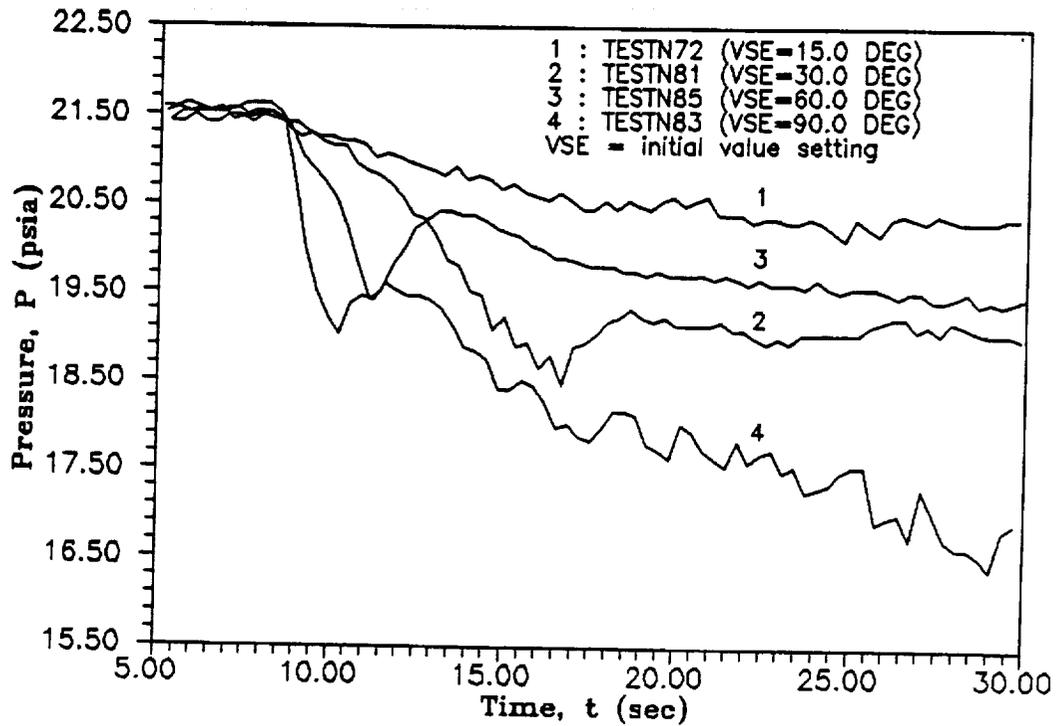


Figure 8 - Pressure Transients During Sudden Depressurization for Different Discharge Rate

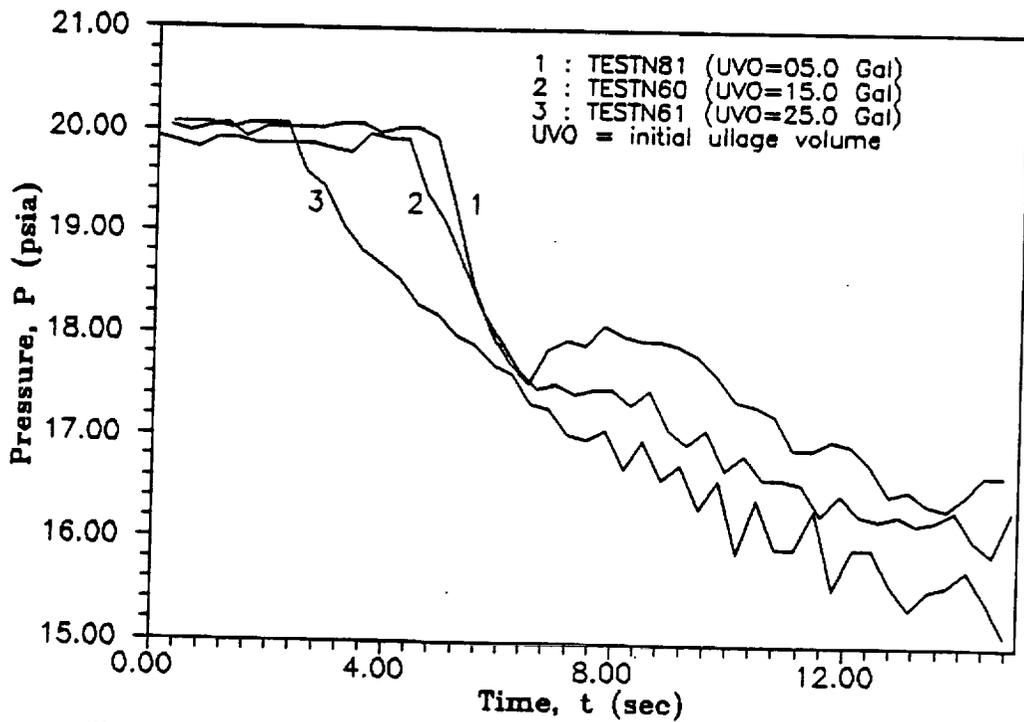


Figure 9 - Pressure Transients During Sudden Depressurization Different Initial Ullage Volume

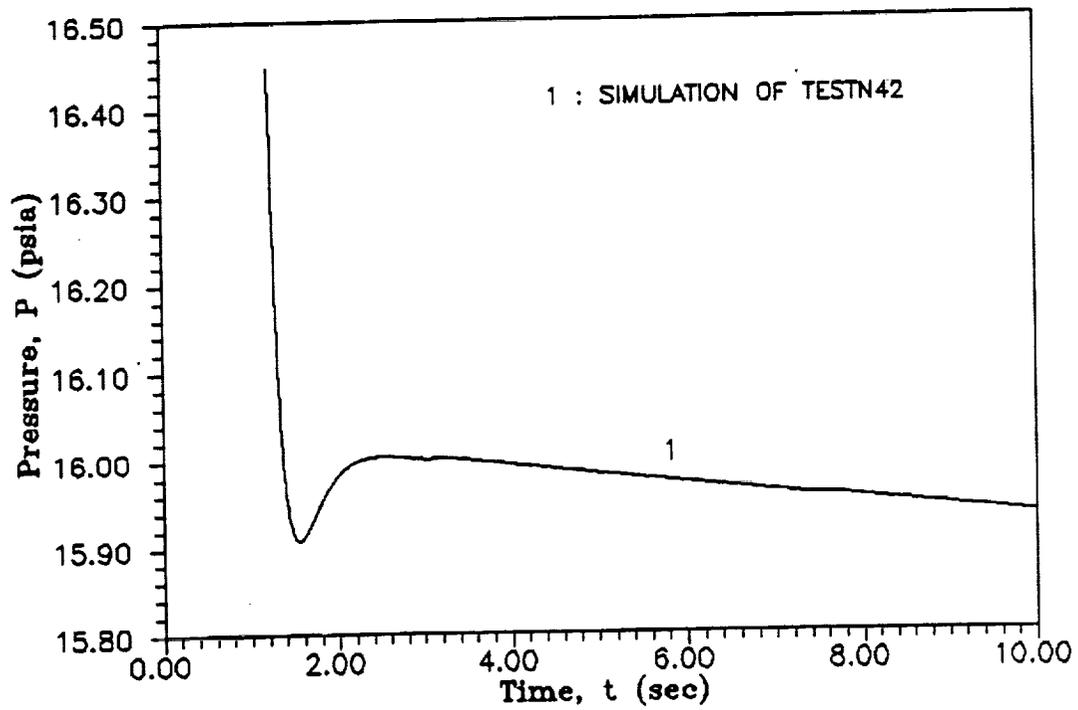


Figure 10 - Numerical Simulations of Pressure Transients in Vapor

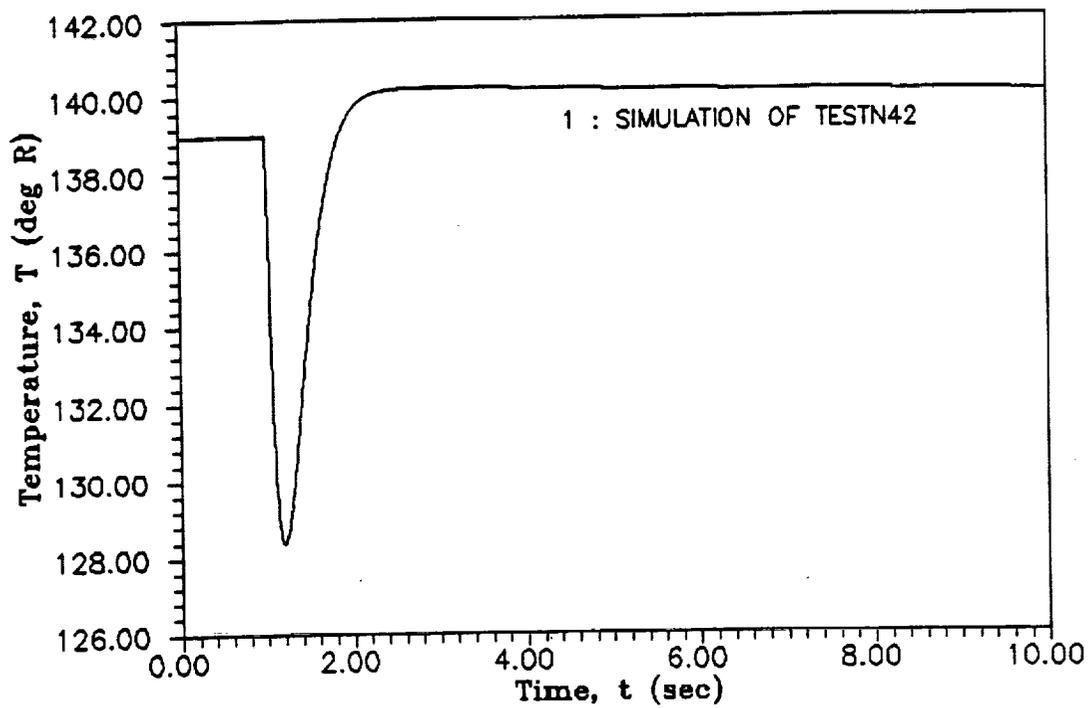


Figure 11- Numerical Simulation of the Temperature Transients in Vapor